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Construction Engineering Research Laboratory

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Development of a Joint Tightness Parameter for Sheet Pile Structures

A Geometry-Based Method for Comparative Estimation of Leakage Through Different Sheet Pile Interlock Configurations

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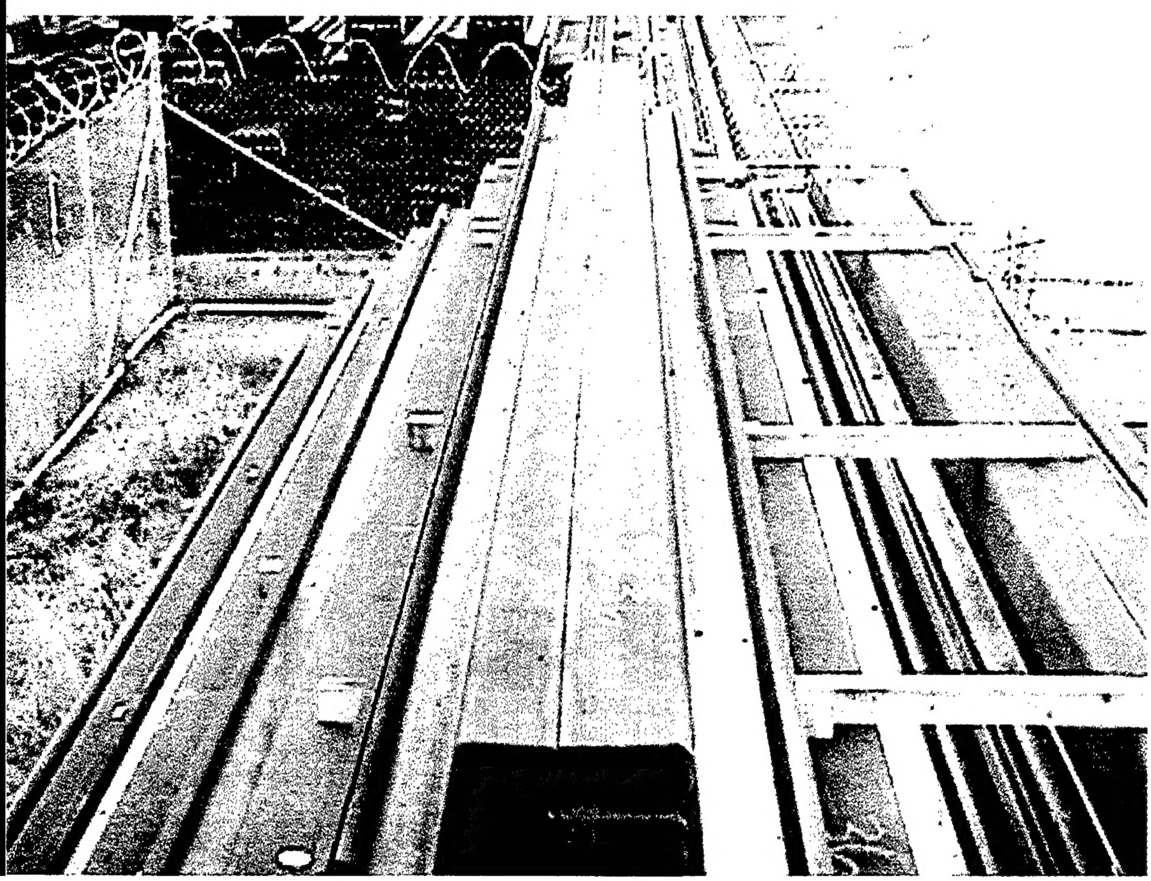
April 2002



Foreword

This Special Report was prepared for Headquarters, U.S. Army Corps of Engineers (HQUSACE), to document portions of a study conducted for U.S. Army Engineer District Seattle under Military Interdepartmental Purchase Request (MIPR) W68MD991903560, dated 12 July 1999; Reimbursable Work Unit IT9, "Corrosion Study for Wyckoff." The Technical Monitor for the original Seattle District study was M. Kathy LeProwse, CENWS-PM-HW, and the Technical Monitor for HQUSACE was Jim Chang, CECW-EW.

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. Charles P. Marsh. The technical editor was Gordon L. Cohen, Information Technology Laboratory – Champaign. Martin J. Savoie is Chief, CEERD-CF-M, and L. Michael Golish is Chief, CEERD-CF. The Technical Director for this work unit was Dr. Paul A. Howdyshell, CEERD-CV-ZT, and the Director of CERL is Dr. Alan W. Moore.

CERL is an element of the Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL John W. Morris III, EN, and the Director is Dr. James R. Houston.

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1 Introduction

Background

The amount of leakage through sheet pile interlock joints is of interest to the U.S. Army Corps of Engineers for a number of applications. Previous work has looked at various aspects of this problem (Telling, Menzies, and Simons 1978; Fitts 1997), and physical measurements of leakage have been made for specific situations (Sellmeijer et al. 1995). During sheet pile service life, a number of factors will affect the leakage rate, including (1) original interlock configuration, (2) stress state, (3) corrosion, (4) physical and/or biological fouling, (5) temperature, and (6) pressure differential across the interlock joint. For purposes of engineering sheet pile structures it would be useful to have a defensible method for quickly developing estimates of relative leakage among the various options being considered.

In the course of previous work conducted for U.S. Army Engineer District Seattle by the Army Engineer Research and Development Center, the Construction Engineering Research Laboratory (ERDC/CERL) developed a simple method for estimating the relative joint tightness in order to compare the leak-tightness of two or more specific sheet pile interlock designs. Although the technique was created to help provide an objective basis for comparing several project-specific sheet pile joint configuration alternatives, it was recognized that the technique could have a wider utility in properly selected applications — especially those where a fast judgment is required and conducting physical leakage tests is not feasible.

Objectives

The objectives of this report are to:

1. document a simple method for developing a comparative estimate of overall joint tightness against leakage for two or more specific interlock configurations and spacings
2. describe through example how the method may be applied.

Approach

Flow through an interlock joint is approximated as a series of linearly connected channels through which laminar flow occurs. It is assumed that there are no losses at entry or exit, and that the pressure gradient is constant. In order to produce a conservative estimate that would account for the maximum possible flow through a joint comprising new material of a given interlock design, a theoretical non-stress or 'neutral' configuration is used in which it is assumed that no contact occurs within the joint. In reality, at various places within a sheet pile structure, the joints will be jammed shut, pulled open, or distorted in any number of non-predictable ways due to driving, ground motion, etc. For estimation purposes over the entire structure, it is assumed that effects increasing flow through a joint in some places would approximately be neutralized by effects restricting flow elsewhere in the structure.

Scope

Results based on this method have not yet been correlated to actual experimentally determined leakage measurements. Therefore, at this time, the main value of this method is in its ability to provide a geometrically derived comparison of leak-tightness for two or more sheet pile interlock configurations. In other words, the joint tightness parameter is intended to provide a rough comparison of different interlock designs in terms of joint leakage, not a comprehensive engineering model.

The key factors affecting leakage — interlock channel length and width — are accounted for in the method. The technique falls within the capabilities of any Army Engineer District, requiring only some simple measurements from interlock specimens and the application of some basic algebra. To facilitate use of this technique a District might require vendors bidding on a sheet pile construction project to provide diagrams of interlock cross-sections and include all necessary measurements.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 cu in.	=	16.39 cm^3
1 cu ft	=	0.028 m^3

2 Description and Application of a Joint Tightness Parameter

Procedure for Assessing Relative Sheet Pile Joint Tightness

The flow through a sheet pile bulkhead interlock joint is assumed to be a regular and smooth fluid motion. This is often called laminar flow when no turbulence is involved. For low Reynolds numbers (i.e., a characteristic number that identifies a fluid flow situation as laminar, transitional, or turbulent), this is also known as *Poiseuille* or *Hagen-Poiseuille Flow*. When applied to a channel that is modeled as being infinitely deep, of length L and width 2a, the net result for mass flow rate is found to depend on the channel width cubed divided by the channel length, as follows:

$$\frac{dm}{dt} = \frac{2\rho a^3 (P_1 - P_2) w}{3\eta L}$$

where:

m = mass
□ = fluid density
$P_1 - P_2$ = pressure difference
□ = viscosity
w = vertical distance

In order to determine a geometrically derived joint tightness parameter (JTP) for a sheet pile interlock, each joint configuration is considered as a series of linearly connected channels through which water flows in a laminar fashion.

Before measurements are taken, a joint sample must be prepared as follows. After rough sectioning with a cutting torch or other means as needed, a cross-sectional sample is cut from two interlocking pieces. The cross section should be perpendicular to the longest axis of the original individual sheet pile to within 10 degrees. The cut surface must be everywhere parallel, clean, and without significant imperfec-

tions. One method of sectioning is to use a wet abrasive cutoff wheel. Filing of sharp edges resulting from sectioning is allowed, but no *in situ* bulk metal may be removed. Alternatively, a digitized trace or accurate computer-assisted drawing of the sample joint also can be used.

For measurement purposes, the two independently moveable pieces that make up the interlock joint are positioned in a neutral stress state. In this position, no joint surfaces are expected or assumed to touch although some separations will typically be quite small. During the entire measurement procedure, this relative position between the two pieces must remain fixed and unchanged. If the relative position of the pieces is changed during a measurement, then all measurements taken up to that point become void, and the positioning and measurement process must be repeated.

For linear or curved segments the individual lengths, L_n , are measured along the center of the channel. By summing all individual segment lengths a total channel length will be calculated as follows:

$$L_T = L_1 + L_2 + L_3 + \dots\dots\dots + L_n.$$

For each individual segment a characteristic or average cross sectional width, a_n, shall be measured. It is expected that all measurements performed will have an accuracy that is within at most 10% of the value obtained. For an individual channel of varying width multiple measurements that are uniformly spaced along the channel shall be taken and the mean valued used as characteristic. Included in such multiple measurements will be values for both the widest and narrowest portion of the channel. In order to account for multiple sequential channels of varying length each characteristic width measurement will be weighted according to the proportion of length it characterizes. An effective total width shall be calculated as follows:

$$a_T = (L_1/L_T)\, a_1 + (L_2/L_T)\, a_2 + (L_3/L_T)\, a_3 + \dots\dots + (L_n/L_T)\, a_n$$

Using the two parameters for effective total width, a_T, and total interlock channel length, L_T, the JTP shall be calculated as follows:

$$JTP = (a_T)^3 \;/\; L_T$$

In order to perform a relative comparison of interlock joint tightness, each of the JTP factors determined for differing interlock joint configurations are to be directly compared. For sheet pile configurations that have identical open joint spacings (i.e.,

not welded shut or permanently sealed in some other fashion), the joint configuration with the smallest or lowest JTP value is considered the tightest joint. For comparison purposes, this parameter is first expressed or converted into identical units of length squared (e.g., square millimeters, or mm^2).

For relative values that are within 20 percent of each other (as derived from the difference relative to the smaller value), a consistent and uniformly applied error analysis comparison must be performed to see if the two values have any overlap of their cumulative measurement band of error (i.e., plus or minus the differential of error estimation). If any overlap occurs, then those two JTP factors shall be considered identical for selection purposes.

For comparison of sheet pile configurations in which the horizontal spacing (i.e., distance) between interlock joints is not identical, then a per-unit or normalized, width-modified JTP (MJTP) shall instead be used. The value for this comparison is calculated using the open joint spacing, S, as follows:

$$\text{Width-Modified JTP} = \text{JTP} / S$$

For comparison of MJTP values, a similar cumulative measurement analysis is required, but only if they are within 10 percent of each other (as derived from the difference relative to the smaller value). As before, the smallest or lowest MJTP value shall be considered to indicate the tightest joint.

JTP Application Example

Description of Samples

Three different samples of sheet piling were used for analysis. Each sample consisted of two interlocking pieces. These pieces were cross sections of much longer piles and each was approximately 1 ft in height. Figure 1 – Figure 3 show the differing interlock joint configurations.

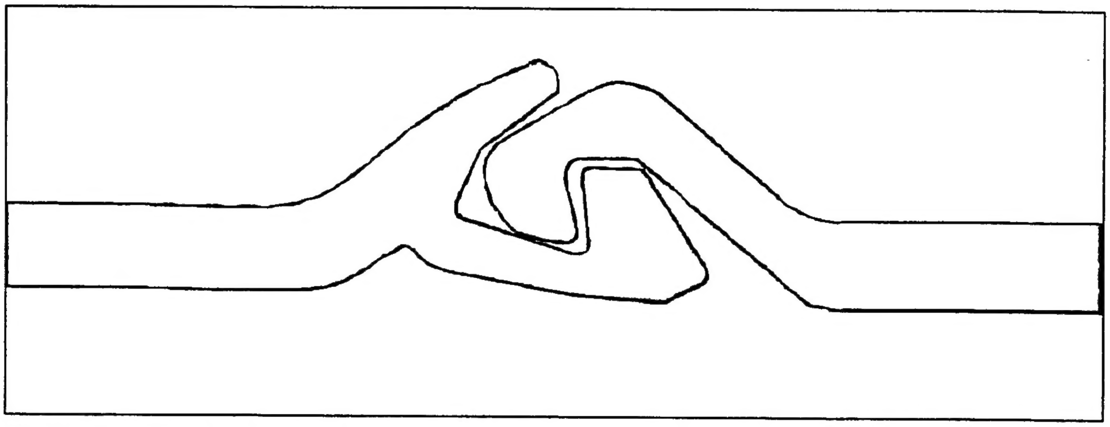

Figure 1. Sample 1 cross section.

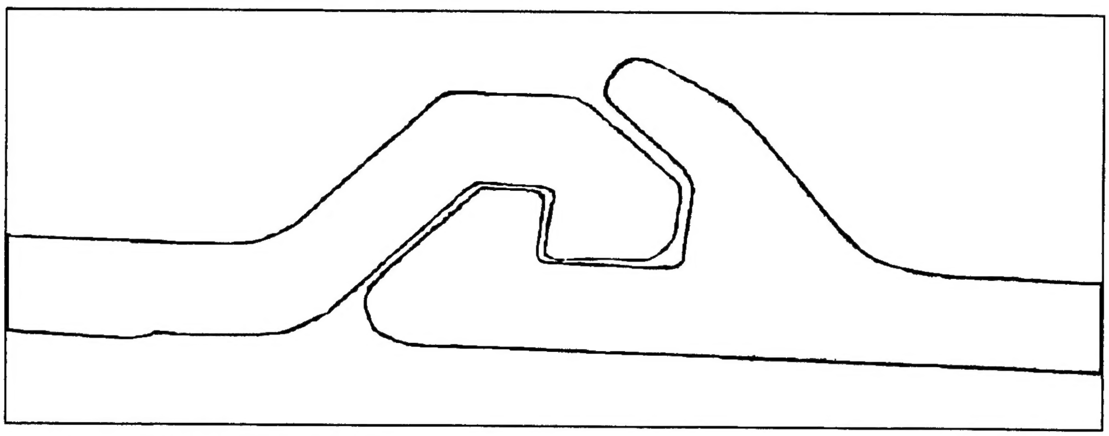

Figure 2. Sample 2 cross section.

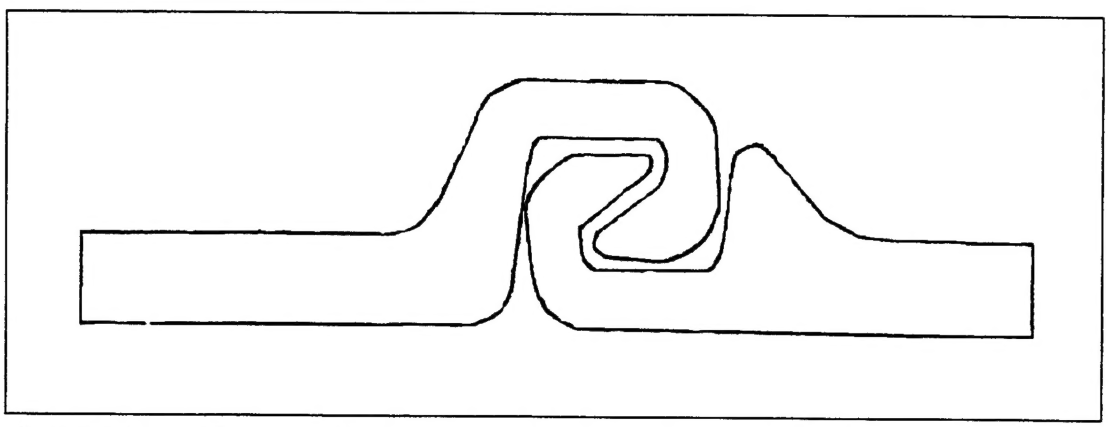

Figure 3. Sample 3 cross section.

Sample Preparation

First, both pieces of each sheet pile sample were interlocked as designed. A cutting torch was then used to cut a combined section of the joint measuring approximately 3 in. by 10 in. Once this section had cooled in air, a wet abrasive cutting wheel was used to prepare a cross-sectional sample of the interlock joint measuring approxi-

mately 0.5 in. in height by 8 in. in length. These samples were then glued to 0.125 in. thick metal plates in a neutral (i.e., no-stress) position and allowed to dry. Specifically, in this procedure, a neutral position is defined as one in which (1) no surfaces touch and, (2) to the greatest extent possible, the spacing widths of the various segments that make up the total path through the joint are equalized.

Measurement Procedures

Each interlock joint was considered as eight separate, sequential segments that were designated either as straight or curved. For each segment, a total of eight width measurements were taken at equally spaced intervals in order to arrive at an average (i.e., mean) characteristic width value for that segment. Measurements of segment lengths were also taken. The measurements associated with each interlock joint segment were recorded on an individual data form. For each sample, eight data forms were used to document a total of 72 measurements (64 for width and 8 for length). All measurements were taken with a Starrett* dial micrometer (Model No. 120) with demarcations every 0.001 in. A typical uncertainty value associated with a measurement was 0.01 in.

Summary of Example Measurement Results

Table 1 – Table 3 summarize the measurement results for the three samples. It should be noted that the characteristic segment widths and the associated uncertainties are calculated values, and so an additional digit is carried through the calculations, and truncated later so as to preserve an appropriate level of accuracy.

Table 1. Summary of measurement results for Sample 1.

Segment No.	Length (in.)	Uncertainty (in.)	Characteristic Widths (in.)	Uncertainty (in.)
1	0.557	0.02	0.0845	0.0125
2	0.595	0.025	0.1396	0.0300
3	0.646	0.01	0.0776	0.0113
4	0.315	0.02	0.1048	0.025
5	0.734	0.02	0.1133	0.0113
6	0.576	0.02	0.1166	0.0100
7	0.495	0.025	0.1359	0.0300
8	0.435	0.02	0.0834	0.0200

* The L.S. Starrett Co., Athol, MA.

Table 2. Summary of measurement results for Sample 2.

Segment No.	Length (in.)	Uncertainty (in.)	Characteristic Widths (in.)	Uncertainty (in.)
1	0.861	0.02	0.0971	0.01
2	0.483	0.02	0.110	0.005
3	0.350	0.03	0.2038	0.02
4	0.824	0.01	0.042	0.01
5	0.405	0.01	0.0586	0.01
6	0.205	0.03	0.0634	0.0163
7	0.338	0.02	0.0349	0.005
8	0.673	0.01	0.0601	0.01

Table 3. Summary of measurement results for Sample 3.

Segment No.	Length (in.)	Uncertainty (in.)	Characteristic Widths (in.)	Uncertainty (in.)
1	0.395	0.02	0.0829	0.01
2	0.238	0.02	0.0609	0.015
3	0.942	0.03	0.160	0.0325
4	0.405	0.01	0.038	0.0313
5	0.121	0.03	0.1039	0.03
6	0.442	0.02	0.1166	0.02
7	0.430	0.02	0.0795	0.02
8	0.885	0.035	0.1609	0.0213

JTP Example Calculation Results

As described on page 8, the JTP is defined as follows:

$$JTP = (a_T)^3 \; / \; L_T$$

where L_T is the total interlock joint channel length and a_T is a length-weighted, total effective interlock joint channel width. Using the values from Table 1 – Table 3, these are calculated as follows:

$$L_T = L_1 + L_2 + L_3 + \dots\dots\dots + L_n.$$

$$a_T = (L_1/L_T)\, a_1 + (L_2/L_T)\, a_2 + (L_3/L_T)\, a_3 + \dots\dots + (L_n/L_T)\, a_n$$

The results of these calculations, without yet accounting for differences in interlock joint spacing distances, are shown in Table 4. The smallest calculated value for JTP is for Sample No. 2. The uncertainty values shown in Table 4, and those for all calculation results in this summary, are the result of applying standard methods of the calculus of variations involving partial differentiation (Kaplan 1973, to cite one of many possible examples).

Table 4. JTP results for the three samples.

Sample Number	JTP x 10^{-4} (in. ^{2})	Uncertainty x x 10^{-5} (in. ^{2})
1	2.86	6.49
2	1.24	2.47
3	4.22	13.2

The Appendix demonstrates the calculation for one example in detail.

Width-Modified JTP (MJTP) Example Calculation Results

In order to compare two or more sheet pile configurations in which the horizontal distance between interlock joints is not identical (i.e., the individual piles are of different width), it is necessary to employ a width-modified JTP, or MJTP. This is done by dividing by the intended horizontal spacing, S, between open joints. The results of these calculations are shown in Table 5. Since no measurement uncertainty is reported for S by any of the sheet pile fabricators, a value of 0.05 in. is assumed for all. Again, the smallest calculated value for the MJTP is for Sample No. 2.

Table 5. MJTP results for the three samples.

Sample Number	S (in.)	Modified JTP x 10^{-6} (in. ^{2})	Uncertainty x x 10^{-8} (in. ^{2})
1	24.81	11.5	2.32
2	16.75	7.41	2.21
3	22.64	18.6	4.11

Measurement Uncertainty Analysis

Introduction

As explained previously, each interlock joint was considered as eight separate, sequential segments that were designated as either straight or curved. For each segment, a total of eight individual width measurements were taken at equally spaced intervals along the length of the segment. These measurements were then averaged to arrive at a characteristic and representative width value for that segment. Length values were also measured for each segment. For each of these two types of measurements, an associated uncertainty value also was determined. These uncertainties were then used in subsequent calculations to estimate an uncertainty associated with the final results.

Individual Error Estimate

As before, all measurements were taken using a Starrett dial micrometer (Model No. 120). Once a value was measured and noted, the micrometer settings were then varied while maintained in the same location so as to definitely and discernibly be both too long and too short. The difference of these latter two numbers from the actual measurement were then determined and averaged. This average value of the differences was then considered to be the uncertainty of that particular measurement. The uncertainties ranged from 0.005 to 0.04 in. A typical uncertainty was within the range of 0.01 in. to 0.03 in. Table 6 and Table 7 show the average uncertainty values for width and length measurements, respectively. Since the width, even for an individual segment, is assumed to vary (which in fact turned out to be the case) the use of a 'standard deviation approach' would not be applicable. Standard deviations are applicable for multiple measurements of a single fixed value.

Table 6. Averaged uncertainty values for width measurements.

Type of Width Segment	Average Width Uncertainty (in.)	Number of Measurements
Straight Widths	0.0143	144
Curved Widths	0.0176	48
Both Combined	0.0173	192

Table 7. Averaged uncertainty values for length measurements.

Type of Length Segment	Average Length Uncertainty (in.)	Number of Measurements
Straight Lengths	0.0181	18
Curved Lengths	0.0283	6
Both Combined	0.0206	24

Determination of Associated Error

As explained previously, various parameters are defined that involve using the original measured widths and lengths to calculate a result. These values are average width for an individual segment, total length, total characteristic width as weighted and normalized by segment length, joint tightness parameter, and a width-modified joint tightness parameter. All of these calculated quantities are associated with a formula or function. It also was noted that the individual, functionally dependent influence of uncertainty in any independent variable can be accounted for through the use of differential calculus. Take for example a completely general function, $Z = f(x, y)$, where the independent variables are x and y. If the function Z has continuous first partial derivatives within the applicable domain, then Z has a differential defined by:

$$dZ = \left(\frac{\partial Z}{\partial x}\right)\Delta x + \left(\frac{\partial Z}{\partial y}\right)\Delta y$$

at every point within that domain. For current purposes, Δx and Δy represent the uncertainties associated with the independent variables, and the differential, dZ, becomes the overall error associated with that particular calculation. Through repeated application of the approach above, one finds for the current example:

3. the differential for the averaged width measurements within a single segment,

$$da_n = \sum_{i=1}^{8} \frac{(\Delta a_i)}{8}$$

4. the differential for the total length,

$$dL_t = \sum_{n=1}^{8} (\Delta L_n)$$

5. the differential for the total characteristic width as weighted and normalized by segment length,

$$da_t = a_t \left(\sum_{n=1}^{8} \left(\frac{a_n \times \Delta L_n}{p}\right)^2 + \sum_{n=1}^{8} \left(\frac{\Delta a_n \times L_n}{p}\right)^2 + \left(\frac{\Delta L_t}{L_t}\right)^2 \right)^{\frac{1}{2}}$$

where "p" is defined as

$$p = \sum_{n=1}^{8} a_n L_n$$

6. the differential for the joint tightness parameter,

$$dMJTP = MJTP \left(\left[\frac{\Delta JTP}{S}\right]^2 + \left[\frac{\Delta S}{S}\right]^2 \right)^{\frac{1}{2}}$$

and

7. the differential for the modified joint tightness parameter,

$$dJTP = JTP\left(\left[\frac{3 \times \Delta a_t}{a_t}\right]^2 + \left[\frac{\Delta L_t}{L_t}\right]^2\right)^{\frac{1}{2}}$$

In the sequence of equations above, the variables are defined as:

a_i = individual width measurements for a single segment

a_n = averaged characteristic width value of a single segment

L_t = total length measurement (sum of individual segment lengths)

a_t = total length-weighted and normalized characteristic width

JTP = joint tightness parameter

MJTP = modified joint tightness parameter

s = the length or spacing between open joints.

3 Summary

This report has described a simple, geometry-based model to determine relative sheet pile interlock joint tightness. The model can be used to produce a numerical result called the joint tightness parameter (JTP) which provides a measurement-based indication of comparative joint tightness against leakage. In developing this procedure, the sheet pile interlock joint was modeled as a series of linearly connected channels through which laminar flow occurs. A sample application of the model was presented, comparing three different interlock joint configurations and the associated measurement error.

Future work correlating this approach to experimentally determined leakage rates could provide a well founded and generalized means to quantitatively estimate joint leakage. Such an estimate could be useful in the design phase of any future sheet pile project for which characterizing or limiting inflow or outflow is critical.

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Appendix: Sample JTP Calculation

This appendix describes in detail the mathematical determination of an arbitrarily selected sample's JTP results as shown in Table 4. For Sample No. 2 the channel segment length measurements , in inches (from Table 2), are added up to arrive at total length:

$L_T = 0.861 + 0.483 + 0.350 + 0.824 + 0.405 + 0.205 + 0.338 + 0.673$

or

$L_T = 4.139$ in.

This total channel length is then used to proportionally weight each characteristic segment *width*. The multiplicative weighting factor for each segment width comprises individual segment lengths divided by the previously calculated total length, or L_1 / L_T , L_2 / L_T , L_2 / L_T and so on.

For Sample No. 2 these weighting factors are:

$L_1 / L_T = 0.861 / 4.139 = 0.208$

$L_2 / L_T = 0.483 / 4.139 = 0.117$

$L_3 / L_T = 0.350 / 4.139 = 0.085$

$L_4 / L_T = 0.824 / 4.139 = 0.199$

$L_5 / L_T = 0.405 / 4.139 = 0.098$

$L_6 / L_T = 0.205 / 4.139 = 0/050$

$L_7 / L_T = 0.338 / 4.139 = 0.082$

$L_8 / L_T = 0.673 / 4.139 = 0.163$

To arrive at an effective total width, a_T, each individual characteristic width measured (Table 2) is then multiplied by the corresponding weighting factor and then added up:

a_T = (0.208) (0.0971) + (0.117) (0.110) + (0.085) (0.2038) + (0.199) (0.042) + (0.098) (0.0586) + (0.050) (0.0634) + (0.082) (0.0349) + (0.163) (0.0601)

a_T = 0.020 + 0.013 + 0.017 + 0.008 + 0.006 + 0.003 + 0.003 + 0.010

a_T = 0.080 in.

Once the total length, L_T, and the effective total width, a_T, have been determined, then the JTP can be calculated. The JTP is found by cubing the effective total width and dividing by the total length:

$$\text{JTP} = (a_T)^3 / L_T$$

Using values for Sample No. 2, the calculation is as follows:

$$\text{JTP} = (0.080 \text{ in.})^3 / 4.139 \text{ in.}$$

or

$$\text{JTP} = 1.24 \times 10^{-4} \text{ (in.}^2\text{)}$$

which is also shown in Table 4.

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14. ABSTRACT

The amount of leakage through sheet pile interlock joints is of interest to the U.S. Army Corps of Engineers (USACE) for a number of applications. For engineering purposes it would be useful to have a defensible method for quickly developing estimates of relative leakage among the various sheet pile options being considered. During the course of a USACE project involving sheet pile construction, a simple, geometry-derived method was developed for estimating the relative leak-tightness of two or more specific sheet pile interlock designs. Although the technique was created to help provide an objective basis for comparing several project-specific alternatives, it was recognized that the technique could have a wider utility in properly selected applications — especially those where a fast judgment is required and conducting physical leakage tests is not feasible.

The key factors affecting leakage — interlock channel length and width — are accounted for in the method. The technique falls within the capabilities of any Army Engineer District, requiring only some simple measurements from interlock specimens and the application of some basic algebra. This report documents the logic, calculations, and assumptions underlying the method, and includes a step-by-step sample application.

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